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Numerical simulation of geothermal reservoirs for the sustainable design of energy plants: A review

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ABSTRACT

Numerical simulation is a fundamental instrument for the elaboration and assessment of a strategic utilization of geothermal energy. It can be used for the evaluation of both the natural (unperturbed) state and the production scenarios. The motivation and important role of the numerical models are described here and deeply illustrated in the context of the geothermal energy exploitation. The mathematical–physical background is also briefly illustrated, together with all the practical problems of modeling and implementation. Particular attention must be paid to the boundary conditions and thermophysical parameters assignment and calibration. The reliability of the model must be accurately evaluated, in order to prevent common failures in design and running of the energy conversion units and wells. Several case studies are reviewed and discussed, and a final discussion is presented. The limits of the reservoir modeling and simulation are also outlined in a general methodological perspective of integrated analysis. The scenarios modeled and assessed can be then used as practical tools for the sizing and optimization of the power unit or direct heat utilization.

Contents

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1. Introduction

Geothermal energy is considered a strategic resource in many countries, even if its use appears to be often marginal in the national energy systems. Its continuous operating mode distinguishes geothermal energy from the other renewable sources, intermittent or stochastic. Majority of the geothermal sources worldwide are medium-low enthalpy type (water dominant, at temperature lower than 150 °C and pressure below 15 bars). Stefansson, [1] estimated that more than 70% of the geothermal resources available in the world are water dominated fields, at temperatures under 150 °C. The binary cycle technology with Organic Rankine Cycle (ORC) appears to be the most efficient and convenient solution for such a kind of resource [2]. Binary power plants are now objects of wide attention by energy markets, although their diffusion is still made difficult by a lacking technology standardization and due to the quite high specific costs [3,4]. The great variability of the resource characteristics worldwide is one of the possible reasons. The proper matching between the reservoir capability and the plants parameters (power size, extraction/reinjection rate) is a critical key point. In power plants using dry-steam (high enthalpy) geothermal resources, pressure and temperature reduction can be compensated by an increase of the mass flow rate. In case of binary plants, a variation of the resource properties (T_{geo}, p_{geo}) could also lead to a fast end of life of the plant. The first and most important activity to design a geothermal energy plant is an accurate investigation of the geothermal potential assessment, as well as the prediction of reservoir response at given industrial exploitation configurations. For these reasons, a multidisciplinary approach to the problem of exploitation of geothermal fields (in particular at medium-low temperature) is necessary. Thermal engineering, geochemistry, geophysics, and reservoir engineering are the fields involved in this technique (Fig. 1). The authors have diffusely discussed this topic in a recent paper [5].

Numerical simulation is a fundamental and strongly interacting instrument for plant design [6]. Different approaches are here considered with reference to several case studies of geothermal fields, which are reviewed and discussed. The perspectives of numerical simulation of geothermal reservoirs as support to the design and sizing of geothermal plants are also outlined. Simulation can be very important in order to define and progressively modify the management strategy of the geothermal field. Construction of the numerical model must be supported by a detailed knowledge of the spatial distribution of the properties of the reservoir: the accuracy in the definition of the dataset is fundamental for the construction of the model. The model is then enriched by including the database of historical data collected during exploration.

The results obtained depend a lot on the accuracy level of the input data. The model will be much more accurate if as much details as possible are known about the geological properties of the rocks (effective porosity, density, specific heat, permeability, thermal conductivity), thermophysical properties of the fluid (specific heat, density, thermal conductivity), fractures pattern and layout, natural recharge of fluid, geothermal boundary conditions.

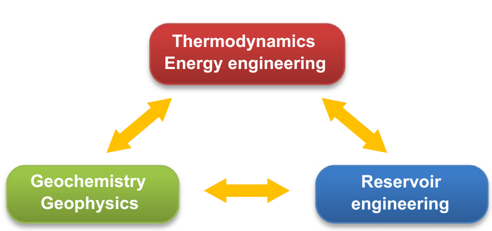

Fig. 1. The multidisciplinary approach proposed, with the connections between the three areas involved.

The numerical model of a geothermal reservoir is very important both for the definition of the geothermal potential assessment and of the reinjection strategy. The geothermal potential of a particular area means the definition of temperature (T_{geo}) and pressure (p_{geo}) of the geothermal fluid and also of the maximum mass flow rate (M_{geo}) that can be extracted maintaining the thermal properties of the reservoir and of the geofluid constant for a long time. Concerning the reinjection strategy, it is necessary to take into account the circulation model of the fluid in the regional area considered [7]. A general methodology for the reinjection technologies is not properly available in literature, the optimal strategy is in fact site-dependant, as the potential assessment itself. Interesting discussions on this particular topic are reported by Sigurðsson et al. [8], and recently by Kaya et al. [9].

The main task of potential assessment and sustainable plants design is the optimization and enhancement of the resource durability (Vaccaro [6]). Interesting contribution on the definition and evaluation of the sustainability and renewability of the geothermal energy uses are available in the recent paper by Hähnlein et al. [10], together with the paper by Axelsson [11]. Particularly in case of innovative geothermal utilizations (like for example EGS) the long-term consequences on the environment are not completely known yet. The same argument can be then referred to the renewability of the resource itself, which is directly dependent on the type and rate of utilization. The renewability (and sustainability) reference level can vary, as one can adjust the energy system size and extraction rate according to an acceptable durability level [11]. Also in case of direct heat utilization (e.g. district heating) some strategy remarks should be pointed out. In the recent paper by Fox et al. [12] the renewable capacity of deep systems is assessed and discussed in order to elaborate a rotating utilization strategy.

The numerical simulation of geothermal reservoirs is a well known topic and has already been an object of investigations and reviews (e.g. O'Sullivan [13]). Unfortunately, till now the use of numerical simulation has not faced any direct connection with the energy systems analysis. A proper prediction should deal with the changes of the different parameters in response to given mass flow rate extraction and reinjection (corresponding to the specific energy strategy). It is evident that a key role is assigned here to the numerical simulation of the reservoir, as compared to other reservoir engineering aspects (wells siting, fluid losses, tracer test). This ambitious task seems to be not of specific interest in most of the analyses carried out in the past, so the authors would like to review the recent developments in the field of numerical simulation of geothermal fields, focusing their attention on the particular use of such an important instrument for the sustainable design of geothermal plants.

2. Numerical simulation of geothermal reservoirs: strategic role for the design of geothermal plants

The numerical simulation of a geothermal reservoir is a well known field of research in the literature and it has already been an object of accurate review analysis and methodological overview [13–17].

Two main goals can be identified: history matching and forecast of future scenarios (consequent to the exploitation of the reservoir). History matching is usually done to check the reliability of a model and evaluate the sustainability level in retrospect. It is the analysis of an exploitation history according to the data log until present time or during a particular time interval. This also allows to check the numerical model in a

"feedback loop" and calibrate or adapt it to what is reported in the history data (in order to improve future scenarios forecast). This is practically done by assigning temperature and mass flow rate of both the geofluid extracted and reinjected, and any other useful historical data recorded that can be translated into thermophysical parameters or boundary/initial conditions. Some phenomena which affect the behavior of field utilization could not be put into a simulation in a proper way, without knowing about them from the history (natural recharge, natural change of the pathways of circulation into the rock formations, losses of pressure, etc.). If a model is considered to be reliable, it can be used to study how the durability of the resource changes depending on different extraction rates, reinjection temperatures, wells siting, fractures (also induced). A productive strategy can be based on the results of a model simulation. This is true for both power plants and thermal energy direct uses. Some general and macroscopic aspects of the application of numerical simulation to the geothermal energy study are listed here:

- equations describing the phenomena considered (circulation, energy/mass transport);
- estimation of the main thermophysical parameters;
- boundary conditions (BC);
- geothermal potential assessment;
- coupling between the power/thermal utilization and reservoir.

2.1. *Characterization of the geothermal source potential*

Potential assessment is a fundamental step of a geothermal project and its final goal is the sustainable utilization of the resource. It involves the complete characterization of the field, energy stored, maximum fluid rate, useful temperatures and chemical parameters of the fluid (to determine the minimum temperature for reinjection). This evaluation is surely important for each kind of water dominant geothermal field, but mainly in case of moderate temperature geothermal fields in which the installation of an ORC plant is programmed. During the running of a plant the productivity (and wells deliverability) can show some remarkable variations (in terms of flow rate, fluid chemistry and specific enthalpy of geofluid). These changes can be addressed to reservoir pressure decline because of excessive fluid production. The reservoir fluid pressure is also another important parameter, linked both to the productivity of the well and the scaling phenomena. High pressure in the geofluid pipes can keep the scaling phenomena under controlled rates.

2.2. *Reinjection strategy and geofluid chemistry*

Only if reinjection is practiced one can say that geothermal energy is being used as a renewable energy source. The practice of reinjection avoids temperature and pressure decline in a geothermal field. For the binary power plants it is a basic approach for resource management and it appears to be compulsory. The task is the optimization and enhancement of the durability of the resource: the argument has been diffusely analyzed in [6]. The objectives that this practice has to achieve are essentially the efficient restitution of the geofluid to the reservoir in order to optimize the recharge in terms of enthalpy and flow rate, and choosing the correct siting and depth of the wells to guarantee a sustainable use of the resource. The optimum reinjection strategy is a quite complex task and it strongly depends on the type of geothermal system (Kaya et al. [9]). In general the minimum temperature values are in the range between 60 °C and 80 °C.

The siting of production and reinjection well and their mutual interference are the main issues of the strategy. To give a trivial example: if they are too far, the recharge could occur in a long time interval (longer than the plant lifetime). If they are too close a cold fluid short-circuiting could occur. A correct reinjection strategy has to take into account the thermodynamic and chemical problems of the scaling phenomena, which in many cases increase with lowering of the temperature. Early study of the geothermal system is fundamental, in order to avoid the worst consequences of fouling, corrosion and clogging of the parts of the plant, of the pipings, and the "tapping" of the wells.

3. Numerical simulation of geothermal reservoirs in the integrated approach to sustainable design

Numerical simulation of geothermal reservoirs allows us to understand the hydrogeological behavior and heat transport into the reservoir under a certain utilization rate. It is possible to study the geothermal reservoir by solving the balance equations of mass, momentum and energy in the particular volume in which hydrothermal circulation of fluid occurs. The hydrogeological issues linked to the geothermal exploitation (knowledge of the geological structures and of the groundwater system) must be connected with the engineering tasks of the design and optimization of the energy conversion system. The constitutive laws are peculiar for each kind of reservoir, while the numerical analysis issues are also important in order to achieve a reliable solution. The development of the numerical model itself has to follow two main directions:

(1) The unperturbed (or undisturbed) natural state.
(2) The utilization scenarios (during the exploitation).

Different phases in the development of the model can be identified. A first "block-structure" has to be built together with the dataset of the parameters which best fit what it is expected by the conceptual model. This first step model should reproduce:

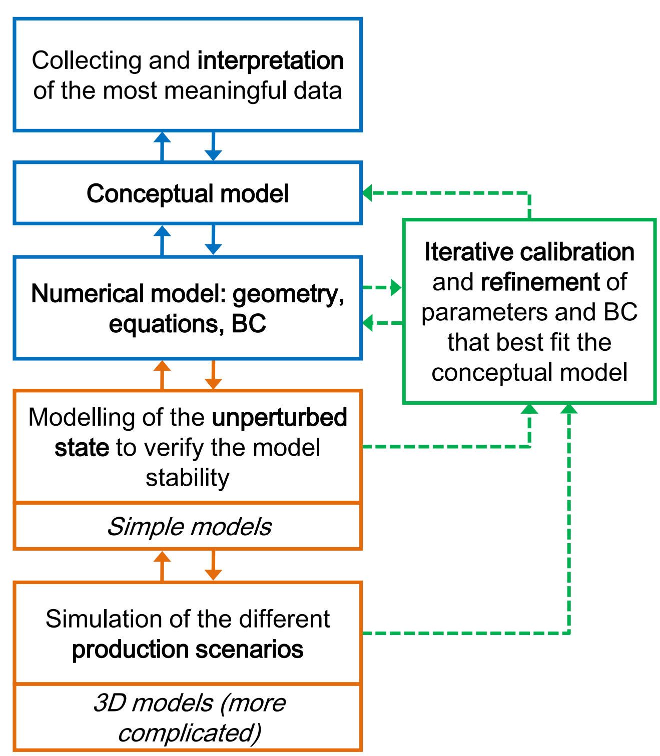

Fig. 2. Conceptual scheme for the elaboration of a numerical model of a geothermal reservoir.

- Geological structure of the reservoir.
- Geometrical features of wells and fractures.
- Hydraulic, Thermal, Mechanic and Chemical conditions (HTMC).

3.1. Conceptual model and numerical model

The conceptual scheme for the realization and simulation of a model of a geothermal reservoir is represented in Fig. 2 (modified after [14]). If a numerical model is realized in a multidisciplinary team or environment it happens that who is in charge of building up the model is not totally aware of the conceptual model of the field. It then becomes necessarily a work of a team in which different geothermal backgrounds and experiences are shared. An important step of “interpretation” and appropriate data collection must be pursued firstly, for the elaboration of the conceptual model (Huenges [15]). This first step model should reproduce: geological structure of the reservoir; geometrical features of wells and fractures; Hydraluic, Thermal, Mechanic and Chemical conditions (HTMC).

The model should then pass a further step of calibration and refinement. It is an iterative process, in which the parameters and boundary conditions should be adjusted according to the conceptual and physical model previously elaborated and to the uncertainty level of part of the database used. Some thermophysical properties (permeability, thermal conductivity, porosity, specific heat capacity) change with siting, depth and hydrothermal alteration. Their value can be adjusted and the mesh can be refined at this step.

A first model of the unperturbed state is the result of the attempts described here. It should be run for a long simulation time interval (10^5–10^6 years) in order to verify the model stability and convergence. In case of strong uncertainty about both the heat transport phenomena and geophysical data, simple 2D models (or lumped parameters models) could be firstly run. Exploitation and energy utilization scenarios can be then run starting from the unperturbed state simulation as initial conditions. The renewability assessment and durability of the resource have to be results of the scenarios simulation. In particular, temperature and pressure should be kept stable in the reservoir as much as possible. If chemical properties and saturation curve of the specific geofluid mixture are known, scaling and chemical deposition phenomena can be also introduced in the calculations, in a multi-physics simulation environment. The models can couple different transport equations, referring to mass, heat and chemicals. It is important to remark that in the results of the simulation some effectively useful data for the plant design must be extracted. It is evident that some of the geophysical and general results are not directly necessary or relevant for who is in charge of designing the plant. A close interaction between who elaborates the numerical model and who designs the utilization plant would be needed (according also to the considerations and remarks about interdisciplinary work and sustainability assessment discussed in the previous chapters).

From a practical point of view, building a numerical model of a geothermal reservoir is not that easy. With respect to other engineering or science systems, a reservoir cannot be practically measured in all its features. Its evolution can be studied, and a model can represent a way of behavior prediction only if it is based on reliable data. In Fig. 3 a conceptual scheme about how the development of numerical models can help the sustainability assessment is shown. The size of the geothermal area must be known, the geometric domain must be big enough to comprehend every interesting mass/energy transfer boundary or spot, but also small enough to reach a proper calculation time. Present softwares and mesh generators allow to set up very complicated geometries (also polygonal), but it is a good point to start with simple mesh types and domain shapes (e.g. quadrangular, radial). A mesh refinement can be useful only for the area interested by mass/energy transfers, like wells, natural recharge, atmospheric geothermal manifestation. Anyway the problem of calculation time saving must be considered, as it can occur for the operator to think about a massive refinement, on domains which are too big. Once the geometry and mesh have been set up, the equation parameters (and constitutive law) must then be considered. The constitutive law (e.g. Darcy Law) is typical for each phenomena,

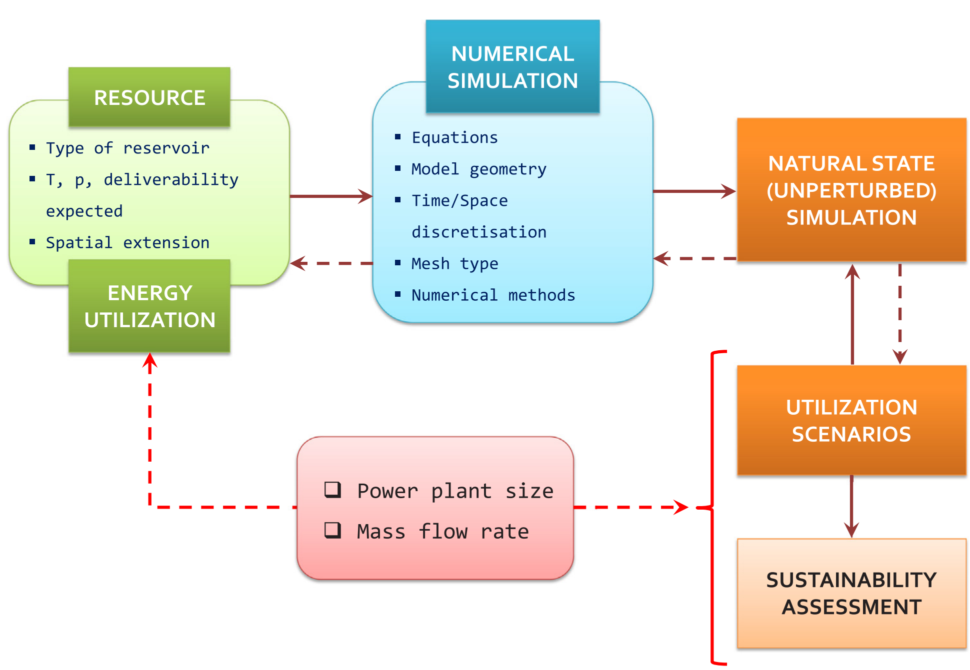

Fig. 3. Information flow and prospect for the sustainable assessment through the use of the numerical simulation of the reservoir.

the conceptual model must arrange and properly describe the transport phenomena occurring in the geological system. Thermo-physical parameters should then be put into the simulation. It is a big problem, as the hypothesis of homogenous material is useful but it has some practical limitations. One single value of a significant parameter like porosity or permeability is assigned to a layer, or element (maybe with irregular shape). Often one has no possibility of assigning tensors or directional parameters (e.g. preferential directions for circulation), as they derive from very accurate measurements and interpretations. Calibration is a good tool, as it allows to address parameter values matching with real temperature and pressure data. Anyway it is possible only when reliable measured data are available. The main parameters to be assigned are essentially:

- porosity (ϕ, defined as the ratio between the voids and the total volume considered) and effective porosity (taking into account all the "interconnected" voids, allowing then the fluid circulation);
- permeability (k), being property of both the rock and the circulating fluid, giving an idea of the productivity of such a rock formation;
- density (ρ, its distribution derives from accurate measurements and usually it is approximated with a single value for each rock formation);
- thermal conductivity (of both rock and fluid),
- specific thermal capacity (of both rock and fluid).

The simulation is then run, and several well known algorithms can be used. The mathematical/engineering background is also a part of this very complex process. As the task is the sustainability of a project, a proper time scale should be identified, considering both economic lifetime (20 up to 50 years) and natural (or induced) renewability of the resource itself. Usually the steady (unperturbed) state is also simulated, to reach the conditions before the exploitation (in case of new fields). In this case the time scale is very large (10^4 up to 10^7 years). Large part of the models are used to simulate industrial scenarios of power/heat production and study the reservoir response during time. Different strategies can be adopted, in order to keep the utilization feasible and sustainable. It is very important to define the size of the installation (power plant, district heating) only after the simulation and complete resource assessment, this being a result of a sustainable exploitation strategy, not the starting point (Fig. 3). Oversizing or resource fast depletion (reservoir cooling, wrong reinjection) can be some consequences of incorrect sizing.

3.2. Mathematical and physical background

From a mathematical point of view, the studies about transport in reservoirs or aquifers were born in the field of mining engineering, oil and gas and applied thermodynamics. The task is to understand the response of a porous or fractured system when a hydraulic gradient is applied. Anyway the application of some experimental concepts to the geothermal fields is not a trivial task. The hypothesis and the real situation of the field should be compared very carefully.

The basic calculations executed by the softwares for numerical simulation substantially deal with the resolution of the flow into porous and/or fractured media. Equations of conservation of the following properties are solved: mass, momentum, energy, concentration of pollutant (or chemicals) dissolved. Some constitutive laws must also be implemented, dealing with the particular phenomenon involved. Geothermal reservoirs fluid flow can be generally studied according to the Darcy Law about porous media, the Darcy fluid velocity q is defined as (Saeid et al. [18])

$$q = \frac{k}{\mu}(\nabla p - \rho g \nabla z) \tag{1}$$

where k is the intrinsic permeability, being proportional to the hydraulic conductivity K according to the definition (in [18])

$$K = kg\frac{\rho}{\mu} \tag{2}$$

In which ρ is the density, g is the acceleration of gravity and μ is the viscosity, p is the pressure and z is the vertical coordinate. One thing to be considered is that in case of anisotropy an hydraulic conductivity tensor $\vec{K}$ can be defined

$$\vec{K} = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{pmatrix} \tag{3}$$

This element is important in order to consider the complexity of the phenomena involved. Average scalar values of the hydraulic conductivity or permeability are often assigned, but the real behavior of rock formations can be very different from an averaged parameter. For example, porosity also changes with pressure and depth, it is important to understand which assumption must be done when assigning an average value to an extended rock body (having for example an unknown fractures field). The fractures are particularly difficult to reproduce in a numerical model, their accurate description is important if their spatial extension is to be compared to the rock formation size, otherwise average properties can be considered. In the most common reservoir simulation softwares, like for example TOUGH2 [19], it is also possible to define different models for the relative permeability (R_l) as a function of the liquid saturation in the mixture (geothermal fluid) (Petrasim Manual [20]).

Let us now consider a single phase (liquid) flow in a geothermal system. According to Rybach and Muffler [17] the following assumptions have to be considered:

- rock matrix is homogeneous and isotropic, in particular referring to porosity, permeability and thermal conductivity (supposed to be independent by temperature);
- incompressible fluid; with density (ρ) and kinematic viscosity (ν) dependent by temperature according to the laws:

$$\rho = \rho_0[1 - \alpha(T - T_0) - \beta(T - T_0)^2] \tag{4}$$

$$\nu = \nu_0 \sigma(T) \tag{5}$$

with ρ_0, ν_0, α, β and T_0 being opportune constants, while $\sigma(T)$ is a function of T. Pressure work and dissipations due to viscosity can be neglected, internal energy of liquid (l) and solid matrix (r) being

$$E_l = c_{l,vol}(T - T_0) \tag{6}$$

$$E_r = c_{r,vol}(T - T_0) \tag{7}$$

with $c_{l,vol}$ and $c_{r,vol}$ specific volumetric heat capacities of rock and liquid. Under these assumptions the balance equations of mass, momentum and energy can be written respectively as (according to [17]):

$$\nabla \vec{q} = 0 \tag{8}$$

$$\left(\frac{\nabla p}{\rho_0}\right) + \alpha(T - T_0)\left[1 + \frac{\beta}{\alpha}(T - T_0)\right]\vec{g} + \frac{\nu_0 \sigma}{k}\vec{q} = 0 \tag{9}$$

$$[(1-\phi)\rho_r c_r + \phi \rho_0 c_v]\frac{\partial T}{\partial t} + \rho_0 c_v \vec{q} \cdot \nabla T = \nabla \cdot (k_m \nabla T) \tag{10}$$

k_m being the thermal conductivity of the mixture solid liquid.

A double phase system, in which the vapor phase is also considered, is described by similar equations [17]. The following assumptions about porosity have to be done in this case:

- porosity ϕ only depends on local pressure of fluid;
- liquid and vapor phases are in local thermal equilibrium.

The equation of conservation (respectively) of mass, momentum (liquid and vapor) and energy can be then written as follows:

$$\frac{\partial}{\partial t}(\phi\rho)+\nabla\cdot(\rho_l\vec{q}_l+\rho_v\vec{q}_v)=0 \tag{11}$$

$$\vec{q}_l=-\frac{R_l\vec{k}}{\mu_l}\cdot\left(\nabla p-\rho_l\vec{g}\right) \tag{12}$$

$$\vec{q}_v=-\frac{R_v\vec{k}}{\mu_v}\cdot(\nabla p-\rho_v\vec{g}) \tag{13}$$

$$\frac{\partial}{\partial t}[(1-\phi)\rho_r E_r+\phi\rho E]+\nabla(\rho_l E_l\vec{q}_l+\rho_v E_V\vec{q}_v+p\vec{q}_l+p\vec{q}_v)$$
$$=\nabla(k_m\nabla T)+(\rho_l\vec{q}_l+\rho_v\vec{q}_v)\cdot\vec{g} \tag{14}$$

where E is the internal energy of the liquid–vapor mixture, $\vec{k}$ is the permeability tensor and R_l is the relative permeability of the i-th phase ($i=l$, g liquid or vapor). Some fundamental differences between the flow in porous and coherent media than in fractured media must then be taken into account ([7,17]):

(a) permeability induced by fracturing is generally higher than average formation permeability;
(b) fracturing permeability is usually anisotropic (it depends on fracturing preferential direction);
(c) the permeability due to fracturing is considerably more dependent on pressure and tension field in the rock with respect to rock matrix permeability.

In the recent paper by Zeng et al. [21] a discussion about the methods for fractured systems simulation is given. Geothermal fracture systems can be represented essentially in two ways:

(1) discrete fracture network method (fracture orientation, spacing and mechanical properties);
(2) equivalent continuous porous media method (the fracture system is seen as an equivalent continuous media, with similar methodologies as for double porosity and double permeability).

In Fox et al. [12] an analytical and numerical model for fractured reservoirs (multi-fractured EGS) is presented and simulated. In the following Fig. 4 an example of simplified scheme of fluid circulation into the fractures is shown (b being the fracture size and x_s the fractures mutual spacing). There is also the possibility of coupling thermal-flow problems with chemical or geomechanics problems into the same numerical simulation. It is the case of some models presented in literature, like for example the case of a fully-coupled flow and geomechanical model by Hu et al. [22].

3.3. Boundary and initial conditions

The structural–physical model has to be set with the boundary and initial conditions, and also with constraints that can be useful for the results stability. The thermal boundary conditions (BC) usually represent the heat geothermal source entering the reservoir: heat flow from the bottom, fixed temperature values at bottom/top or intermediate layers and adiabatic/impermeable conditions. BCs usually also represent the natural manifestations, natural recharge, lateral or regional flows, wells withdrawal/reinjection in the aquifers and hydraulic head both for the hydrological problem and for the heat transfer. The BC kind are similar when considering flow or heat transport. Fig. 5 provides

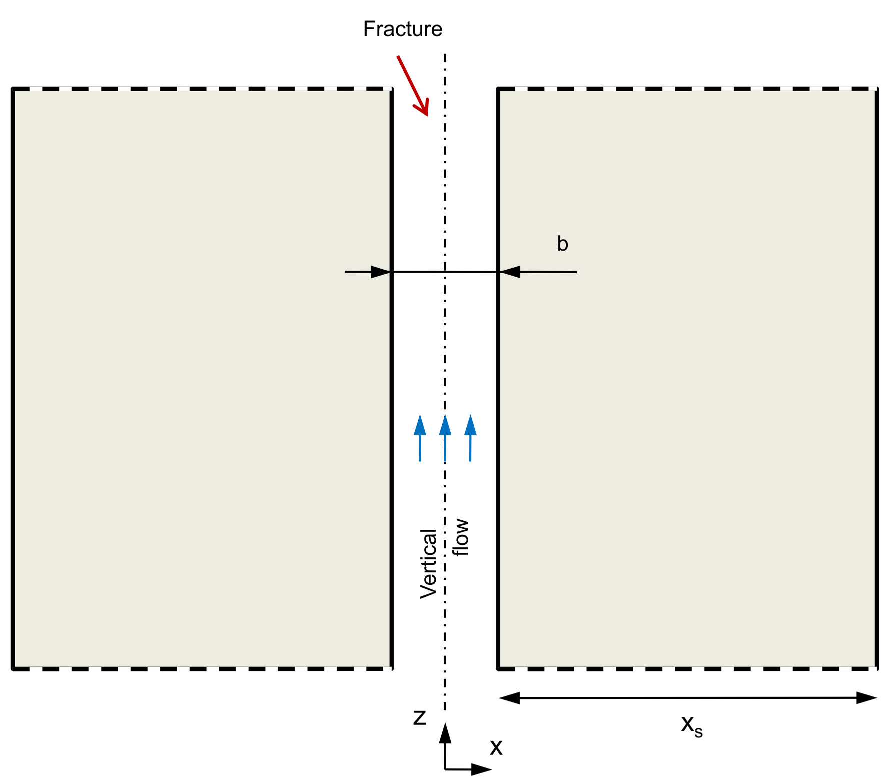

Fig. 4. Conceptual scheme for multi-fracture vertical geothermal system (x_s is the spacing between fractures, b is the fracture aperture).

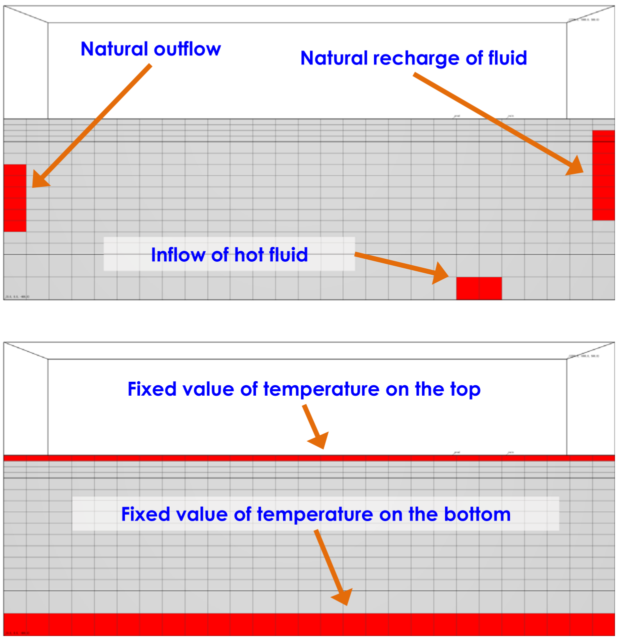

Fig. 5. Example of boundary conditions (both thermal and mass conditions) in a 3D numerical model grid.

example of boundary conditions in a 3D grid. Mainly four types of BC are used:

(1) *First kind* (*or Dirichlet*) *condition* – along a border or a boundary the hydraulic head or temperature are assigned.
(2) *Second kind* (*or Neumann*) *condition* – along a border or a boundary the fluid or heat flux is assigned.
(3) *Third kind* (*or Cauchy*) *condition* – transfer coefficients are used particularly for the hydraulic head.
(4) *Fourth kind condition* – single well or singular point source, typically used for wells conditions (extraction or reinjection, according to the sign convention), implementing Dirac δ function.

In particularly dry reservoirs, conduction is the prevalent mechanism of heat transfer. In hydrothermal aquifers and traditional geothermal systems convection flow also contributes to the mass/heat transport phenomena. Thermophysical parameters database are also available in the most used codes. Anyway, as it is stated in this work, a characterization of the parameters should by site-dependent in order to obtain reliable and physically consistent results.

The initial conditions are usually the thermal gradient, pressure distribution in the domain and hydraulic head levels of rivers or reservoirs. To hold the results range near a specific value, constraints about max/min fluid rate, pressure or heat flow can be set. Fig. 6 summarizes the various steps described here: first the definition of geological elements and dimension of the reservoir, then spatial discretization and materials calibration, finally the definition of boundary conditions, initial conditions and definition of temporal domain.

3.4. Numerical integration of the equation systems

The integration of all the interdisciplinary inputs and procedures is the most challenging and crucial part of a modeling process. An important issue of this process deals with the quality of information and data flowing through the starting phase and the simulation itself. Numerical simulation must be treated and used as an iterative process, continuously changing and improving, as the information flow goes both ways (Ungemach et al. [14]). A good and reliable model is often an object of discussion and reinterpretation. There are different techniques for space discretization: finite difference, finite volume methods, as well as finite element methods. Different numerical integration techniques are implemented in codes and softwares. TOUGH2 [19] for example, uses a finite difference (time fully implicit) discretization, while in Feflow [24] finite element techniques are used. Other softwares are used in literature and in industry. Many softwares have been developed and used by Research Institutes or Universities. In those softwares a lot of the most known resolution algorithms (from numerical analysis and calculus) are implemented. The mesh refinement is a fundamental instrument that can be adopted to improve the analysis and optimize the computational tasks (concentrating for example the mesh number in the wells area or along the faults). Different techniques can be adopted for modeling of the faults, but the accuracy about the data in input (upflow/downflow, fluid rate, permeability, thermal anomaly) for these structures has to be very high to achieve reliable results.

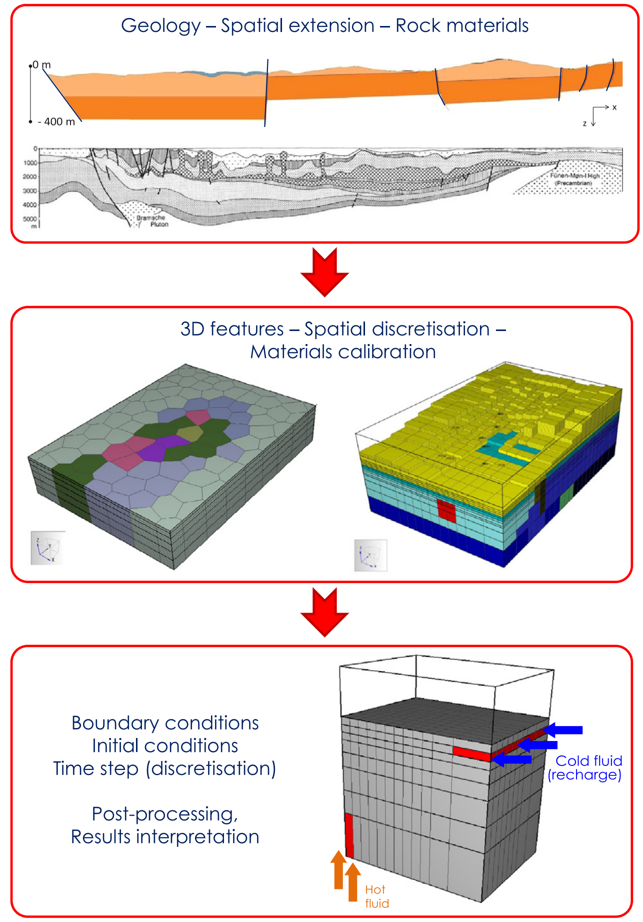

Fig. 6. Overall graphic view of the numerical simulation process (the second vertical geological section is from [23]).

All the most used softwares are multipurpose, involving the possibility of simulating different types of diffusion phenomena. Pre and post-processors are typically embedded in commercial softwares, so that graphical interface and elaboration of the data can be easily carried out. The various design tools (also for shallow systems) are mainly based on the line-source model and Eskilson's approach, and the duct ground storage model DST (Haberl and Do [25]). When coupling of more phenomena is implemented it can give a very useful contribution for the scaling phenomena limitation (concentration, inflow–outflow, and variation during withdrawal–reinjection must be known).

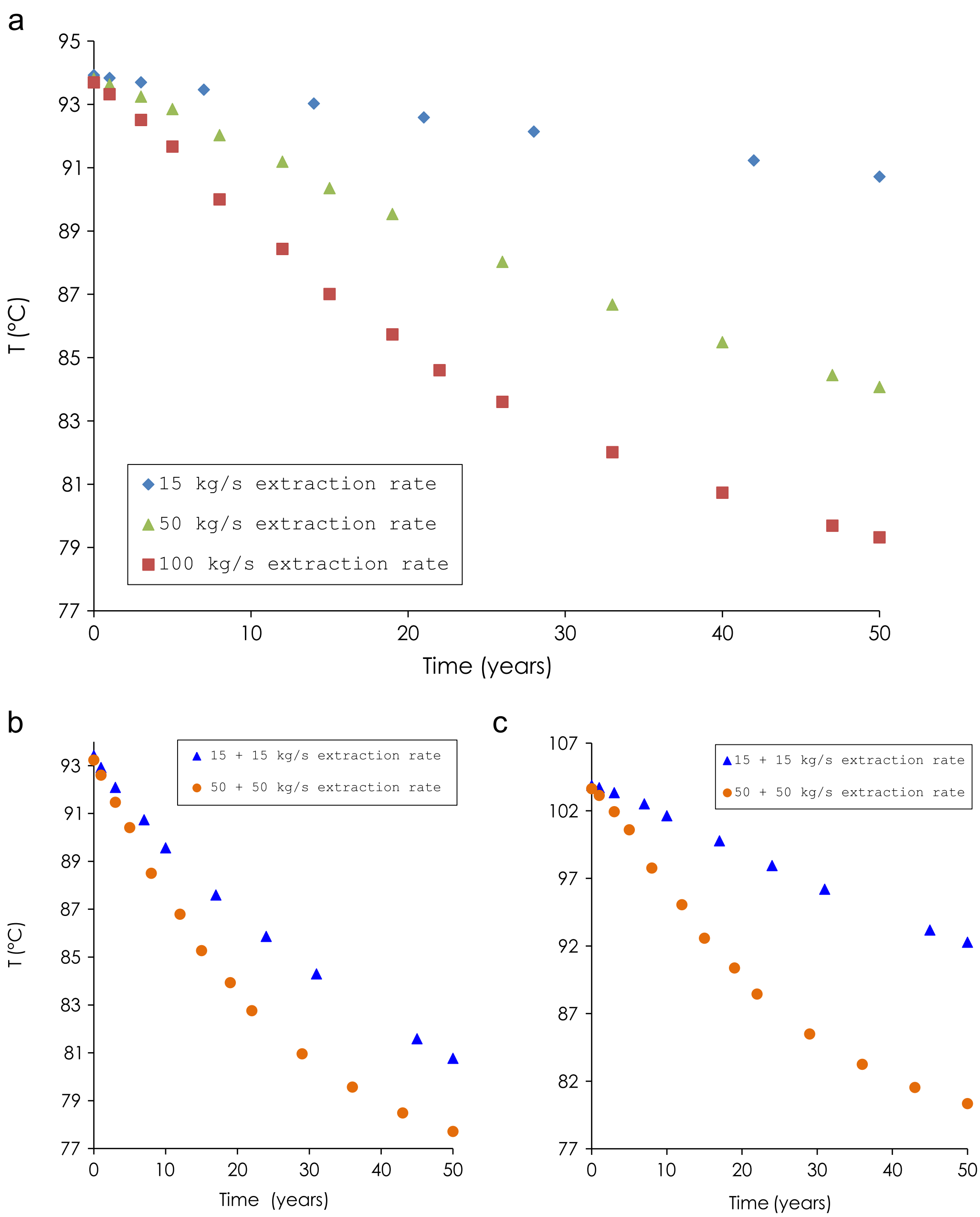

Fig. 7. Typical dotted breakthrough temperature profile: (a) single extraction well; (b) and (c) double extraction well.

3.5. Limitations and criticalities of numerical simulation of geothermal reservoirs

Notwithstanding its strategic importance it is clear that numerical simulation of geothermal reservoirs has some important limitations (which are treated and discussed in this work):

- it strongly depends on the reliability and accuracy of the data;
- numerically stable models can be physically inconsistent.

The first limit can be also expressed by the principle "trash in–trash out". It must be clear which is the physical–numerical problem to recourse numerical simulation for. One should evaluate if the numerical simulation is the more appropriate instrument to face a specific problem. Usually a problem can be simplified in a proper way to be solved according to calculus or numerical analysis without using dedicated softwares and complicated geometric domains. Reservoir model simulation has to be pursued only if it is the most suitable and appropriate way to elaborate a design strategy. "Lumped parameters" models can be very useful for some medium-low temperature fields, considering plain lithological layers. Sometimes, particularly for linear and simple problems they can be satisfactory, in spite of more sophisticated elaborations.

One possible risk is to start "asking too much" or "asking too bad response" to the numerical models, making them "too much" or "too less powerful". For example, starting from the same geological features of a field, a model can give different results depending on the resolution of the spatial distribution of the data. The numerical analysis could be important in order to define the exploitation scenario (Figs. 7 and 8) or the reinjection strategy.

Some typical problems due to incorrect initial characterization of the resource can also be faced with an appropriate model simulation, they can deal with: oversizing of the plant (leading to

excessive extraction), scaling (causing corrosion, productivity drop, diameter reduction) and wrong reinjection strategy (losses of fluid or cooling of the reservoir).

4. Numerical simulation of geothermal reservoirs: a review of case studies referred to experimentally investigated geothermal fields

In this part of the paper various examples of numerical simulations of geothermal reservoirs are analyzed and critically reviewed. The point of connection among the various reviewed cases is the fact that they are referred to very well known geothermal fields for which a lot of experimental data are also available. Each simulation has its own peculiarity, concerning with dimensional scale, enthalpy level of the reservoir, fluid rate extracted/reinjected, and software used. A summary of the meaningful data is also given. All the cases described are different for various reasons. First of all for the typology of geothermal field: from medium enthalpy water-dominant field to dry-steam dominant field. The differences between the models deal with simulation domains (size ranges from some km up to about 100 km), scenarios simulated (unperturbed or exploitation) and software used.

One concept has to be emphasized in this review: the strong dependence of the results of the numerical analysis on the quality of the inputs and the difficulty that would be afforded in realizing the models. First of all, the data and the geo–thermo–physical parameters necessary are not always available or measurable.

In the next two sections some cases will be analyzed: the review is organized as follows: in the first part are a group of cases related to geothermal field for which a lot of experimental data, boundary conditions are available and it is possible to reproduce the results of the simulation (Table 1). Each case is discussed in detail in a single subsection. A second group concerns cases available in the literature and refers to less investigated (and simulated) geothermal systems. The different techniques of numerical resolution of the equations in the model are also considered here.

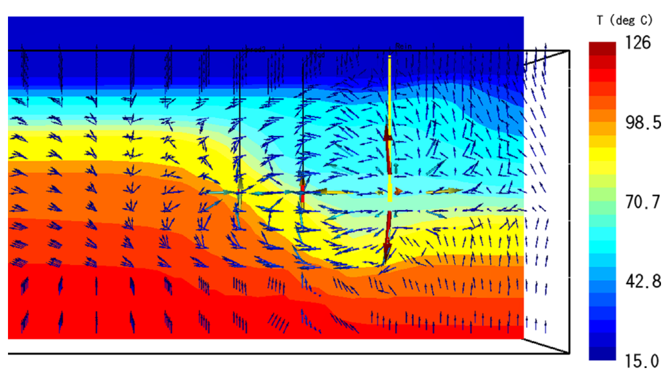

Fig. 8. Graphical results about a simplified single well extraction system (also fluid velocity vectors and iso-temperature vertical section are shown).

4.1. Momotombo reservoir (Nicaragua)

The first case analyzed is the geothermal field of Momotombo in Nicaragua for which a meaningful set of data is available from literature. This case study has been chosen to remark how important the characterization and assessment of the geothermal potential is to undertake a correct industrial exploitation of a reservoir. This analysis is based on the literature data available, mainly from the work of Porras et al. [26–28].

Overestimation of the geothermal potential (and progressive plant oversizing) brought to a gradual and progressive impoverishment of the resource in terms of temperatures, pressures and geothermal fluid rates. Since the initial years of industrial interest (1983–1989) the production decreased and different problems arised. A three-dimensional, porous-media, numerical model of the system was developed and calibrated and it was utilized to study the response of the geothermal reservoir under different fluid production and injection scenarios. The initial hypotheses are: total reinjection of the fluid extracted; reinjection at 100 °C and pressure 5 bars; time-constant fluid rates.

The domain considered in this case is $3.1 \times 2.4\ km^2$ with a total depth of -3000 m, divided into 9 layers. The whole domain is built with 972 blocks (minimum dimensions $200 \times 200\ m^2$, maximum dimensions $600 \times 700\ m^2$). The total number of materials considered is 18. The most permeable layer is $5 \times 10^{-11}\ m^2$, in a depth interval between -150 m and -450 m. Four different scenarios of exploitation, dealing with different extraction/reinjection strategies are proposed. In [26–28] the authors state that satisfactory agreements were obtained between measured and computed discharge enthalpies and flow rates, for most of the shallow wells. The model also qualitatively reproduced the pressure drawdown measured in selected wells.

4.2. Ngatamariki geothermal field (New Zealand)

The Ngatamariki geothermal field is located 17 km from Taupo (North Island, New Zealand). It is one of the several high enthalpy geothermal systems within the Taupo Volcanic Zone (they are more than 20). Exploration wells were first drilled in 1985–1986, and Mighty River Power then drilled further wells in 2008–09. The

Table 1
Summary about the various numerical model analyzed: data referred to experimentally investigated reservoir.

Reservoir	*Software*	*Domain size and blocks no.*	*Mean res. T* [°C]	*Fluid flow rate*
Momotombo (Porras et al., [26–28])	TOUGH2	$3.1 \times 2.4\ km^2$; 3 km depth ; 972 blocks	240–340	~357 kg/s; 13 production wells; 8 reinjection wells (power units: 32 MW)
Ngatamariki (Burnell and Kissling [29])	TOUGH2	$10.5 \times 11\ km^2$; ~5 km depth; 24128 blocks	80 (scenario A); 120 (scenario B)	~695 kg/s (2 scenarios)
Larderello 1 (Romagnoli et al. [30], Barelli et al. [31], Arias et al. [32])	TOUGH2	$70 \times 70\ km^2$; ~7.5 km depth; ~10000 blocks	200–300 °C	1300 kg/s (average historical data)
Larderello 2 (Della Vedova [33])	SHEMAT	$42 \times 26\ km^2$; 10 km (total thickness)	200–300 °C	(Only natural state simulation)
Wairakei (O'Sullivan et al. [34,35]; Mannington et al. [36,37])	Non-commercial codes; TOUGH2	$30 \times 30\ km^2$; 3.4 km (total thickness); 8055 blocks (2006 model)	250 °C (Wairakei–Te Mihi)	~1460 kg/s (historical average); > 200 wells (57 years) (power units: > 200 MW)
Groß Schönebeck (Blöcher et al. [39])	FEFLOW	~$4.8 \times 5.5\ km^2$; ~0.6 km depth; 489591 prism elements; 254744 nodes	150 °C (125 °C after 30 years simulation)	~21 kg/s doublet of wells from the same drilling area
Mt. Amiata (Barelli et al. [40])	TOUGH2	$1100\ km^2$; > 5.7 km (total thickness)	150–220 °C (first shallow res.); 300–350 °C(deep res.)	(Natural state simulation; interaction between reservoirs)
Dubti (Tendaho Rift) (Battistelli et al. [41,42])	TOUGH2/ EWASG	~$2.5 \times 3\ km^2$; > 2 km depth	245–290 °C	140 kg/s

company has planned the installation of overall 130 MW electric power output, from a condensing unit and an ORC unit integrated in a combined cycle configuration (to be first run in 2013). The data about this geothermal field are available from a group of industrial reports by Burnell and Kissling (2009), in particular the one about the reservoir model [29], in which a very complete conceptual model can be found. The geothermal reservoir is composed of 3 parts: a shallow aquifer (50–100 m deep); an aquitard in the rock formation of Huka Falls (50–400 m deep), between the surface aquifer and the intermediate one; and an intermediate aquifer, between Huka Falls rock formation and the clay cap. The grid has globally 26 horizontal layers (of different thickness), subdivided into 928 elements, reaching a total number of 24128 blocks. The surface extension of the model is 132 km^2. An inlet of fluid flow (70 kg/s) is considered, entering from the bottom of the model, at a specific enthalpy of 1450 kJ/kg, with an heat flow of 101.5 MW. From the basement a constant heat flow of 11 MW is considered. As constraints, areas with known flow direction and impermeable formations are simulated using fixed state (T_{geo}, p_{geo}) conditions. The validation of the model is based on temperatures and pressure data measured in different wells and on the calibration of other parameters like porosity, permeability, upflow mass and enthalpy, hydraulic connections between the deep reservoir and the groundwater system.

4.3. Larderello geothermal field (Italy), 2010 model

Larderello field (Italy) is one of the most anciently known and studied geothermal areas of the world. This field has been widely drilled and developed, with an almost 100-year-old history in geothermal energy utilization for power purposes. Average fluid production in the Larderello field, after the most recent explorations and improvements is now about 3700 t/h. The exploration extended in the early 1950s to the near Travale field (10–15 km SE of Larderello), which has now increased its fluid production to an average value of 1000 t/h. For this reason, when talking about large scale model of this geothermal system, usually one can talk about Larderello-Travale geothermal field.

A numerical model about the field has been recently realized and improved, increasing the dimensions of the geological domain considered, by Romagnoli et al. [30], Barelli et al. [31], Arias et al. [32]. The model domain extent is 4900 km^2 (70 km each side), with a total thickness of 7.5 km. The grid is made of 10000 cells and 16 vertical layers. The geological scheme refers to five main rock formations: clayey–shaley caprock (0–500 m), fractured carbonate reservoir (500–1000 m), metamorphic reservoir (1000–5000 m) and granitic intrusion as heat source of the system. Sixteen rock materials are considered and an impermeability condition along the boundaries is assigned. Fixed state (time invariant) conditions of temperature are considered at the top (15 °C, atmospheric pressure) and at the bottom of the producing layer (350–400 °C). Natural manifestations and cold inflow from the shallow aquifers are the only interactions with the external environment. The simulation of natural state has been carried out (millions of years as temporal scale) and a simulation of the exploitation history of the field has also been modeled. The historical data of 700 wells have been represented with 20 "virtual" wells. The conclusion of Romagnoli et al. [30] are that only few changes in the conditions of the natural system have been caused by industrial development of the area.

4.4. Larderello geothermal field (Italy), 2008 model

A different model of this field has been proposed by Della Vedova et al. [33]. This model deals only with the natural state of the geothermal system, without considering the industrial exploitation. A very large temporal scale is considered (8–12 millions of years). The extent of the considered domain are 42×26 km^2, with a total thickness of 10 km. The total depth of the model is very high, to include the K-horizons and the data from fluid inclusions. K-horizons are considered to be the main reservoir bottom, corresponding to the 400 °C isotherm; collocated between 3000 m in the Larderello zone and 10^4 m in the Travale zone. The numerical simulator SHEMAT has been tested and validated with the geophysical data available for the upper crust. The mesh cell size is $1 \times 1 \times 0.3$ km^3. The upper surface boundary conditions are 20 °C and 0.1 MPa, impermeable and adiabatic conditions are assigned at the lateral boundaries. The bottom boundary is assumed to be impermeable and at a fixed temperature of 400–600 °C. A sensitivity analysis about thermal parameters is also considered in [33]. The authors remark that a lot of simulation have been run to match a composite target function, due to the uncertainty about several input data (geometry, rock data). The work considered is an example of deep field simulation, oriented to the comprehension of the deep field phenomena more than to a sustainable exploitation approach.

4.5. Wairakei geothermal field (New Zealand)

Wairakei is another well-known geothermal field located in the Taupo Volcanic zone (New Zealand). The extent of the area is almost 25 km^2. A complete report about the industrial history and the evolution of the numerical models can be found in O'Sullivan et al. [34] and Bixley et al. [35]. Fifty years of activity on this field have been reached in 2008. In the period 1958–1990 the power installed was increased up to 140 MW. After 1990 the power installed has approached 200 MW (with the plant of Poihipi, 55 MW). The trend of the specific enthalpy of the geofluid in the field fits the evolution during the years [35]: rise of pressure due to reinjection activity; increase of temperature in the wells in the "Eastern Borefield" and seepage of cold water in the reservoir.

Several models have been proposed and tested for Wairakei reservoir [34]. The models have been used to simulate different scenarios of field development. The common aspects and main characteristics of the conceptual schemes are: big fractures and faults (NE–SW), increasing permeability; two big upflow areas (260 °C at Wairakei, 300 °C at Tauhara); heat flux fixed values as BC, in the range 300–600 MW; two regions at different pressures (high pressure at Te Mihi, low pressure at Southern Wairakei); natural recharge and rainwater infiltrations (1000 mm/year, 5% infiltration). A discussion about the calibration of the model is also reported in Mannington et al. [36,37]. The code iTOUGH2 [38], a TOUGH2 family software for inverse simulation, has been used to support the calibration process of the parameters and improve the match to the field data. Good matching results have been reached when the Tauhara field (strictly connected with Wairakei) has been introduced in the domain of the model. The perspective is to improve a 27886-blocks model (comprehending Wairakei–Tauhara–Rotokawa).

4.6. Groß Schönebeck reservoir (Germany)

A case study about a simulation of an Enhanced Geothermal System (EGS) in a deep geothermal reservoir with hydraulic stimulation is discussed in Blöcher et al. [39]. The geothermal research site of Groß Schönebeck is located 40 km north of Berlin (Germany). This case is presented as an example of well-based hydrothermal problem with a good match with the sustainable energy exploitation issue. A very good approach both to the numerical simulation and to the accuracy of the data is achieved.

The software used for the simulations is FEFLOW [23]. The simulation deals with a doublet of wells. The reservoir is located between −3815 and −4247 m below sea level, in the Lower

Permian of the Northeast German Basin. The hydraulic stimulation is a technology used to improve the productivity of a reservoir by inducing artificial fractures through high pressure fluid injection (water, gel-proppant). Six geological formations are considered, with different lithologies. Two sandstones formations (between −4000 m and −4100 m depth) are the most appropriate for geothermal power production. Natural fracture system is studied to analyze the conceptual scheme of circulation of the water, and to develop the induced fractures layout. The wells have a distance of 28 m at the surface, the injection well is vertical, while the production well is deviated to guarantee a sufficient distance of 500 m between them within the reservoir.

An interesting aspect remarked in [39] is the dependence of the hydraulic properties with temperature and pressure in the reservoir (density, permeability, porosity, thermal conductivity) to be considered as part of the model. Also the total dissolved solids and chemical composition are considered in the whole model. The model has an extension of $4.809 \times 5.448\ km^2$, with a depth of almost 0.6 km. The grid is made by 489591 prismatic elements and 254744 nodes, discretizing 27 spatial layers. The induced fractures are represented by 2D quadrilateral vertical elements. The production well has a fluid rate of 75 m^3/h (∼21 kg/s) at 150 °C with a concentration of solids of 265 g/l. The injection well has the same fluid rate and concentration of solids but the temperature is 70 °C. The quasi-stationary conditions are reached after almost 4×10^4 years of simulation time (hydraulic head levels are matched). A 30 years simulation of the exploitation with the above mentioned wells conditions gives a production temperature drop from 150 °C to 125.8 °C.

4.7. Mt. Amiata geothermal system (Italy)

In a recent paper of Barelli et al. (2010) the Tuscan geothermal system of Mount Amiata is considered [40]. The fields of Bagnore and Piancastagnaio have been explored and drilled (more than 100 wells) for about 50 years. In this field two main reservoirs are present: the first one is in the carbonatic formations, between 500 and 1000 m deep, at average temperature of 150–220 °C; the second reservoir is in the Paleozoic metamorphic basement at depths of 2500–4000 m, at temperatures of 300–350 °C. The Mt. Amiata Volcanic Complex has a total area of 80 km^2. The peculiarity of the model is not only to analyze the exploitation of the reservoir but also to verify the possibilities of interaction between a phreatic aquifer (separated from the shallow aquifer by few hundred meters of impermeable formations) and the geothermal system. Moreover another particular aspect is that the two main reservoirs are characterized by gaseous caps (gas, vapor), in structures named “traps”. This is a peculiarity of Mt. Amiata field, occurring in the definition of the pressure distribution and fluid circulation model. The numerical model considered has been simulated with the software TOUGH2 [19]. The surface extension of the model is more than 1100 km^2, with a total thickness between −4 km and 1.738 km (a.s.l., Mt. Amiata top elevation). A time-constant heat flow (average 400 mW/m^2, with peaks of 600–700 mW/m^2) is the bottom boundary condition. The model is globally closed, referring to inflow–outflow of water. As remarked in [40], the outputs match with the field data.

4.8. Dubti geothermal field (Tendaho Rift, Ethiopia)

The model of the Dubti geothermal field review is based on a paper by Battistelli et al. [41]. The Tendaho Rift was identified as a promising geothermal area since an exploration project of the late 1960s, and early 1970s. More recently (1990s) a drilling and wells-testing activity was carried out to explore and assess the geothermal resource present in the area (central part of Northern Tendaho Rift). The drilling in the area of Dubti plantation confirmed the existence of a shallow geothermal reservoir. The temperature recorded in the drilled wells is in the interval 245–270 °C, while the temperature of the geofluid rising in a fault in the area is about 290 °C (natural manifestations and fumaroles are present in the whole area). Lots of production/injection tests have been carried out in the area, and the paper cited is very detailed about these data and permeability distribution. The Dubti fault is considered to be ascending and upflow hypothesis is at the base of the conceptual model. Horizontal circulation (with eventually two-phase conditions), when crossing permeable layers, is also considered. For the numerical model the software TOUGH2 [19] has been used, implementing the EWASG equation-of-state module developed for water, sodium chloride and CO_2 mixtures (Battistelli et al. [42]). The simple 3D model is extended about 7.5 km^2 with a total thickness of about 2 km. Natural meteoric recharges are considered (coming from the Ethiopian Plateau) together with horizontal and sub-vertical flows. The assumed initial temperature of the hot upflow is 290 °C. Model results and further drillings confirmed the presence of a hot fluid circulation zone at depths between 250 and 500 m in the Dubti area, also confirming the existence of more permeable zones along the Dubti fault. A possible development program is proposed in [41]: an extraction fluid rate of 140 kg/s from the shallow reservoir, for an expected power plant with maximum size 3–3.5 MW (back-pressure or ORC), serving the near region for about 50 years.

5. Numerical simulation of geothermal reservoirs: an “extended” review of the other available cases

In the present section a further review of several numerical simulations is reported. The cases discussed in the previous section and summarized in Table 1 deal with well known geothermal fields and concern mainly with numerical modeling and data matching. The numerical simulations considered are referred to several geothermal fields object of analysis all around the world [21,23] and [43–70]. The additional cases listed in this section often deal with fields which are presented in the same paper together with the numerical simulation. Different softwares are used and various grid shapes and configurations are adopted.

For some of the cases reviewed only a single paper is available, being the experimental data on the field not available, while in the most recent works a large amount of experimental and exploration data are available. Different geographic areas are involved, in order to perform a meaningful worldwide review. Also, different resource types are considered in the range of the medium-high enthalpy. The cases contained in this section have been reviewed in the Doctoral Thesis of one of the authors (Vaccaro [6]). Table 2 illustrates the main characteristics of the geothermal field, namely the type of resource, fluid production, plant productivity (only estimated in some cases), reservoir extent and production depth. Table 3 contains the main indications about the numerical models, the objectives of the simulation, the geometry and extent of the model and grid and the boundary conditions. Some common aspects can be found in the boundary conditions and calibration process (due to the uncertainty about permeability).

6. Discussion about the numerical models reviewed and perspective for utilization in the energy production perspective

As it is evident from the previous review analysis, the numerical simulation of a geothermal reservoir is a well known field in the literature. In Sections 4 and 5 a summary of the cases is reported, they are all different for various reasons. First of all for

Table 2
"Extended review": characteristics of the geothermal fields.

Field name and References	***Resource***	***Production*** (kg/s)	***Plant: Size and Type*** (MW)	***Extent*** (km^2)	***Heat flux*** (mW/m^2)	***Max. prod. Depth*** (m)
Balcova-Narlidere, Turkey; (Gok et al. [43])	Water dominated, 140 °C	20.6[a] (annual avg.)	0	≈ 2		1100
Cerro Prieto, Mexico (Butler et al. [44])	Water dominated, double phase reservoir, 350 °C		620[b]			3000
Den Haag, Netherlands (Mottaghy et al. [45])	Water dominated, single phase reservoir, 70 °C	≈ 42[a]	5 (thermal, estimated)	547	60–70 (63)	2200
Desert Peak, USA (Zeng et al. [21])	EGS system, ≈ 210 °C	≈ 42	2–5 (EGS-derived binary plant, under development)	4.2		1200
German Basin (Vogt et al. [23])	Water dominated reservoir, sandstone reservoir, 87 °C	≈ 42	District heating	25	50–78	2000
Hammam Faraun, Egypt (Zaher et al. [46])	Water dominated reservoir, 70 °C		Plant for desalinization	77	120	
Hammam Musa, Gulf of Suez, Egypt (Zaher et al. [47])	Water dominated reservoir, 70 °C		13 (estimated potential, volumetric method)	45	80	
Hatchobaru, Japan (Yahara and Tokita [48])	Water dominated, double phase reservoir, 240–300 °C	≈ 700 (≈ 500 reinjected)	110	16.5		2300
Heber, USA (Boardmann et al. [49])	Water dominated, double phase reservoir, 200 °C		120[c] (52 effective)			1830
Hengill Area, Iceland (Gunnarsonn et al. [50])	Water dominated, double phase reservoir, 300 °C		330	210		2000
Kamojang, Indonesia (Suryadarma et al. [51])	Vapor dominated reservoir, 230–245 °C	300–424	200	14–21		≈ 1400
Kizildere, Turkey (Yeltekin et al. [52] and Özkaya, [53])	Water dominated, double phase reservoir, 200 °C	250 (10 effective)	20.4			1240
Las Tres Vírgenes, Mexico (Guerrero-Martinez and Verma [54])	Water dominated, double phase reservoir, 250–275 °C		10–14	16.9–20.3		800–1000
Los Azufres, Mexico (Maldonado et al. [55])	Water dominated, double phase reservoir, 240–280 °C, vapor dominated after exploitation	≈ 475	188	≈ 20		1500
Mt. Apo – Mindanao, Philippines (Esberto and Sarmiento [56], Emoricha et al. [57])	Water dominated, double phase reservoir, 300 °C		104			2500
Pauzhetsky-Kamchatka, Russia (Kiryukhin et al. [58,59])	Water dominated, double phase reservoir, 200 °C	250 (38 to reinj.)	6.8	≈ 5	63	1000
Ogiri, Japan (Kunamoto et al. [60], Itoi et al. [61])	1st reservoir (400–200 m asl): water dominated, 50–130 °C. 2nd reservoir (0 m asl): water dominated, double phase, 230 °C	≈ 320 (243 reinj.)	30		432	1800
Olkaria, Kenya (Ofwona, [62])	Water dominated, double phase reservoir, 200–300 °C		121	≈ 80		1600
Onikobe, Japan (Nakanishi and Iwai [63])	1st reservoir, water dominated, two-phase (− 200 to 300 m a.s.l.), 200 °C. 2nd reservoir: water dominated (− 1200 to − 700 m asl), 250 °C		12.5	≈ 1	175	1300
Poihipi – Wairakei, New Zealand (Zarrouk et al. [64])	Vapor dominated	55.5 (19.5 reinj.)	55 (25 effective)			
Sabalan, Iran (Bromley et al. [65], Strelbitskaya and Radmehr [66], Noorollahi et al. [67,68])	Water dominated, double phase reservoir, 140–250 °C		50+50 (planned)	≈ 100	≈ 200	≈ 3200
Sumikawa, Japan (Pritchett et al. [69])	Water dominated, double phase reservoir, 200 °C		0		400	2486
Tanggu District (Guantao field), Tianjin, China (Lei and Zhu [70])	Water dominated, single phase reservoir, 60–75 °C	11–25		533		≈ 2000

[a] The value is referred to a district heating system using the geothermal resource.
[b] In 2000 an upgrade up to 720 MW was planned, a further upgrade to 820 MW was planned for 2012.
[c] Updated at 1996 [49].

the kind of geothermal field: from medium enthalpy water-dominant field to dry-steam dominant field. The differences between the models deal with simulation domains (size and features), scenarios simulated (unperturbed or exploitation) and software used.

One concept has to be emphasized from this review: the strong dependence of the results of the numerical analysis on the quality of the inputs and the difficulty that would be afforded in realizing the models. First of all, the data and the geo–thermo–physical parameters necessary are not always available or measurable. Moreover defining the boundary conditions and initial conditions is not a trivial task.

Initial conditions in the simulation are mostly: current thermal gradient measured; groundwater recharge flow in the reservoir and pressure distribution. The boundary conditions deal with both the hydro-geologic and the thermal problems, regarding essentially: hydraulic head; temperature distribution at the top/bottom of the geometrical domain; heat flow; natural recharge of steam or water; gases diluted in the geofluid and impermeable and adiabatic conditions at lateral faces. All of these conditions can vary with time during the simulated interval.

In each case matching between the forecast and the measured data is then fundamental. The measured data must then be the basis for enhancing and improving the model during the following steps of the project. For most of the listed models and fields it is very difficult to report here a matching between modeled reservoir and real measured data. In many cases the authors of the simulation are different with respect to the utilization plant owner

Table 3
"Extended review": numerical model simulations.

Field name and References	*Simulation*	*Software*	*Geometry*	*Mesh*	*Conditions and parameters*	*Calibration*
Balcova-Narlidere, Turkey [43]	Natural state History matching (5 y) Evolution (20 y, 3 cases)	TOUGH2	3D: 3 × 4 km^2; thick.: 1.53 km (30 to −1500 m asl)	Irregular grid 13 layers 5194 blocks[a]	Deep nat. recharge: 40 kg/s; shallow recharge: 11 kg/s; total heat rate input: 33 MW	k[b] natural recharge
Cerro Prieto, Mexico [44]	Natural state History matching Evolution (30 y, 3 cases)	TETRAD	3D: 11 × 10 km^2 thick.: 3.6 km	7 layers × 1296 cells; 9072 blocks[c]; range size: 0.25–2 km	Top: T=40 °C; Lateral BC: T assigned to second and penultimate layers, lateral heat flux, fluid losses (347.2 kg/s); Bottom: T assigned, nat. recharge 347.2 kg/s (350 °C); ϕ decrease with depth (range 0.176–0.01), fractures have constant porosity $k_{x,y}$ assumed as a logarithmic function of ϕ	k, λ[b] natural recharge
Den Haag, Netherlands (Mottaghy et al. [45])	Natural state Evolution (50 y)	SHEMAT ArgusOne™ (grid)	3D: 22.5 × 24.3 km^2 thick.: 5 km	2.43 × 10^6 nodes 9 geol. units	Top: constant T (11 °C, mean annual) Bottom: constant heat flux (63 mW/m^2); λ depends on T	Heat flux, λ
Desert Peak, USA (Zeng et al. [21])	Natural state Evolution (20 y)	TOUGH2	vertical 2D–3D; height: 400 m; length: 400 m; thick.: 500 m	104 cells (x) 1 cell (y) 104 cells (z) (3 × 3, 3 × 5, 5 × 5)	Reference case: reinjection 1.5 kg/s (60 °C); ϕ=0.2%; k=5 × 10^{-14} m^2; Mass flow rate 50–75 kg/s	Sensitivity analysis to ϕ, k, λ, mass flow rate, T_{rej}, p_0, productivity index
German Basin (Vogt et al. [23])	Natural state Evolution (20 y)	SHEMAT-Suite	3D: 5 × 5 km^2 thick.: 6 km	≈ 1.4 × 10^6 cells (18 sedimentary layers)	Top: 11 °C surface temperature; Bottom: regional specific heat flow 75 ± 10 mW/m^2 (6000 m depth) Adiabatic lateral boundaries	heat flow, temperatures (3D inversion); Stochastic approach to hydraulic properties assignment
Hammam Faraun, Egypt (Zaher et al. [46])	Natural state (10^5 y+3 × 10^4 y for fracture state) Evolution (20 y)	HYDROTHERM	3D: 77 km^2 thick.: 2.5 km	16 layers × (43 × 31) cells (length 100–1000 m)	Top: T, p constant assigned; Bottom: heat flux fixed (120 mW/m^2); Fracture zone conditions	Thermophysical properties determined by previous studies
Hammam Musa, Gulf of Suez, Egypt (Zaher et al. [47])	Natural state (10^5 y+3 × 10^4 y)	HYDROTHERM	3D: 45 km^2; thick.: 3.6 km	11 layers × (28 × 26) cells (length 100–1000 m)	Top: T, p constant assigned (26.7 °C, 1.013 bars)	
Hatchobaru, Japan (Yahara and Tokita [48])	Natural state Evolution (9 y, 3 cases)	[i]	3D: 16.5 km^2; thick.: 2.5 km (1100 to −1400 m asl)	9 layers (thick.: 100–400 m) 7425 blocks	Referred to a trial-error calibration process and further papers cited in [48]	Trial-error calibration process
Heber, USA [49]	Natural state	TOUGH2	3D: 14 × 13 km^2; thick.: 3 km	8 layers × 201 cells (1608 blocks)[d]	Top: T=25 °C, p=0,1 MPa; Lateral BC: impermeable, adiabatic; Bottom: T and p assigned, nat. recharge	k[b]
Hengill Area, Iceland [50]	Natural state (10^4 y) History matching (20 y) Evolution (30 y)	TOUGH2 iTOUGH2	3D: 100 × 100 km^2; thick.: 2.9 km; (400 m to –2500 m asl)	9 layers × 996 cells (8964 blocks)[a]	Top: T=15 °C, p=0.1 MPa[e]; Penultimate layer: nat. recharge 1 kg/s (1500 kJ/kg) Bottom: T and p assigned (≈ 265 °C), fluid flows	k and natural recharge (iTOUGH2)
Kamojang, Indonesia (Suryadarma et al. [51])	Natural state History matching Evolution (30 y)		3D: 49.5 km^2; thick.: 3.6 km	15 layers 12480 blocks		
Kizildere, Turkey [52]	Natural state History matching (17 y) Evolution (12 y, 9 cases)	STARS SAPHIR V.2.30	3D: 840 × 600 km^2; thick.: 1–1.2 km (estimated)	5 layers (8 × 12 cells)		ϕ, k (SAPHIR)
Kizildere, Turkey [53]	Natural state History matching Evolution (10 y, 4 cases)	SUTRA[f] v. 1284–2D	3D: 870 × 720 km^2	29 × 24 cells	T and p constant at boundaries (not specified)	T, p
Las Tres Vírgenes, Mexico (Guerrero-Martinez and Verma [54])	Natural state (7 × 10^5 y) Emplacement of magmatic chambers Evolution (30 y)	TCHEMSYS	3D: 20 × 30 km^2; thick.: 22 km (1900 to −20000 m asl)	I: 6307200; blocks II: 4939200 blocks	Boundary temperature at the value given by the gradient (0.03 °C/km), surface at constant 25 °C	
Los Azufres, Mexico [55]	Natural state History matching (25 y) Evolution (30 y, 2 cases)	TETRAD	3D: 12 × 12 km^2; thick.: 3.2 km (3200–0 m asl)	9 layers × (18 × 26) cells (4446 blocks)[a, c, g]	Top: natural emissions; Bottom: nat. recharge 8.3 kg/s (water at 345 °C)	Rock parameters[b] natural recharge
Mt. Apo – Mindanao, Philippines [56]	Natural state History matching (2 y) Evolution (5 y, 2 cases)	TETRAD	3D: 6 × 10 km^2; thick.: 2.75 km (1250 m to –1500 m asl)	6 layers × (11 × 17) cells (1122 blocks)[a, h]	Natural emissions Bottom: nat. recharge 5 kg/s (320 °C), 10 blocks	k, ϕ natural recharge

Table 3 (*continued*)

Field name and References	*Simulation*	*Software*	*Geometry*	*Mesh*	*Conditions and parameters*	*Calibration*
Mt. Apo – Mindanao, Philippines [57]	Natural state (95×10^6 y) History matching (13 y) Evolution (5 y, 2 cases)	TOUGH2	3D: 22×26 km^2; thick.: 3.25 km (1250 m to −2000 m asl)	19 layers × (31 × 47) cells (27683 blocks, only 16411 active)[a]	Top: 65 °C; 0.1 MPa; Bottom: nat. recharge 145 kg/s (320 °C); Lateral BC: impermeable, adiabatic, outflow from constant pressure cells	k, ϕ natural recharge
Pauzhetsky-Kamchatka, Russia [58]	Natural state History matching (36 y) Evolution (20 y, 3 cases)	TOUGH2 A-Mesh	3D: polygonal [i]; thick.: 0.7 km (avg.)	131 cells × layer Double ϕ model	Top: nat. emiss. 100 °C; Lateral BC: constant T, p; Bottom: heat flux 63 mW/m^2, nat. recharge[n] 204 kg/s (830–875 kJ/kg), (SE) 120 kg/s (900 kJ/kg)	k, p natural recharge rock expansion coefficient
Pauzhetsky-Kamchatka, Russia [59]	Natural state History matching (36 y)	TOUGH2 iTOUGH2 A-Mesh	3D: polygonal[i]; thick.: 0.85 km (100 to −750 m asl)	3 layers (424 blocks, only 294 active) Double ϕ model	Top: atm. T, p; nat. emissions (100 °C); Lateral BC: impermeable, constant T, p; Bottom: heat flux 63 mW/m^2, nat. recharge 224 kg/s	iTOUGH2: T, p, natural emissions, natural recharge ($\dot{m}$, k) History matchng: production wells[h], monitoring wells (T, p), ϕ, k, fractures
Ogiri, Japan [60,61]	Natural state History matching	TOUGH2 iTOUGH2	3D: 5.5×3.9 km^2; thick.: 2.85 km (250 to −2600 m)	7 layers × (23 × 11) cells (1771 blocks)[a, l] cell size: 0.1–3 km (thick.: 0.1–1.6 km)	Top: T=75 °C, p=0.0981 MPa; Lateral BC: impermeable, adiabatic; Bottom: heat flux 43.2 mW/m^2 (432 mW/m^2, S), total heat in 19.5 MW (260 mW/m^2 avg.); nat. recharge:[e] 30 kg/s (240 °C), total inflow (31.4 MW); 55 kg/s (1062.7 kJ/kg, inflow 58.4 MW), production area.	k (iTOUGH2)
Olkaria, Kenya [62]	Natural state (10^4 y)	TOUGH2	3D: polygonal (120 km^2)[m]; thick.: 2.55 km (2000 to −550 m asl)	5 layers × 158 cells (790 blocks)	Top: atm. cond.[e], natural emissions (vapor) 366 kg/s; Lateral BC: E–W impermeable, N p=45 bars, S p=25 bars (1075 m asl); Bottom: nat. recharge 1253 kg/s (6 blocks), 1600 kJ/kg (avg.); fluid loss 958 kg/s.	k[b] natural recharge
Onikobe, Japan [63]	Natural state History matching (21 y) Evolution (10 y, 1 case)	RANGER STAR	3D: 6.5×8 km^2; thick.: 2.4 km (400 to −2000 m asl)	14 layers × (10 × 11) cells (1540 blocks)[a, g, l]	Top: const. patm, nat. emiss.[e]; Lateral BC: N–E impermeable and adiabatic; S–O constant p; Bottom: heat flux 175 mW/m^2, nat. recharge 10 kg/s (330 °C) production area	k[b] natural recharge
Poihipi – Wairakei, New Zealand [64,65]	Prod. Wells	TOUGH2 iTOUGH2 AWTAS[n] WELLSIM			Porous/homogeneous media double ϕ (matrix/fracture) fractional dimension model	k, ϕ (AWTAS, iTOUGH2)
Sabalan, Iran [66–68]	Natural state Evolution (3 cases)	TOUGH2	3D: 12×8 km^2; thick.: 4.6 km	16 layers × 192 cells; 2688 blocks (2565 active)[a, b, c, o]	Top: heat loss to atmosphere; nat. manifestations (modeled as 4 artificial wells, 40–50 kg/s). Second to last layer (near to the base): natural recharge, 8 kg/s at 130 °C. Lateral: impermeable and adiabatic Bottom: nat. recharge, 90 kg/s @ 265 °C (1159 kJ/kg, total 104.31 MW); uniform heat flux: 200 mW/m^2 (Central-Southern area), null in the North area.	K natural recharge
Sumikawa, Japan [69]	Natural state (3×10^4 y) Evolution (50 y, 1 case)	STAR	3D: 3×5 km^2; thick.: 2.8 km (1200 to −1600 m asl)	16 layers × (9 × 10) cells (1440 blocks)[o, p]	Top: atm. cond. (T=10 °C), nat. Vapor emissions Lateral BC: E–W–S impermeable, adiabatic, nat. recharge; Bottom: impermeable, heat flux 400 mW/m^2 (tot 6 MW) Initial: T vertical 10–250 °C	k[b] recharge geology
Tanggu District (Guantao field), Tianjin, China (Lei and Zhu [70])	Natural state History matching Evolution (5 y, 2 cases)	AUTOUGH2	3D: 25×21.3 km^2; thick.: 2.1 km	2 layers × (780 blocks) (thick.: 150–1100 m); Block size: from 250×250 m^2 to 2000×2000 m^2	Water table assigned. Top layer T and p constant (inactive elements). Natural recharge and inflows are assigned.	P thermophysical parameters[b]

[a] Mesh refinement in the production wells zone.
[b] Manual iterative calibration.
[c] Matrix and fracture are both simulated in the cells.
[d] Both quadrangular and polygonal shaped blocks (the last ones are used to simulate the fracture).
[e] Meteoric water recharge is also considered.
[f] SUTRA – Saturated-Unsaturated TRAnsport.
[g] First layer reproduces orography.
[h] Mesh refined at the sea level layers.
[i] 7 sides polygonal area: $2 \times 0.5 \times 3 \times 2 \times 3 \times 1.75 \times 1.5$ km^7.
[l] MINC model applied to the main fault of the geothermal system (MINC – Multiple INteracting Continua).
[m] 7 sides polygonal area: $11 \times 11 \times 5 \times 9 \times 10 \times 2.5 \times 6$ km^7.
[n] AWTAS –Automated Well-Test Analysis System.
[o] Mesh refinement in the atmosphere contact blocks.
[p] First six layers reproduce orography.

while in other cases the history matching can be limited to a quite reduced time.

Let us consider two different cases, the Larderello geothermal field and the Sabalan geothermal field. In the first case (see Table 1, [30–33]) a lot of historical data are available, also from detailed plant production, the simulation described in [30–32] has been realized to study the changes in the large field after years of exploitation and drilling, but it has been done only at the end and not in a forecast mode. For this very famous field it was impossible to think about a strategy as the one proposed here, the numerical simulation being a modern practical solution (the first plant in Larderello has been installed in 1913). In the case of Sabalan (see Tables 2 and 3, [65–68]) the numerical model is done during an exploration step, so the industrial production target proposed has not been verified yet. This is to discuss about the possibility, for some of the fields and models illustrated, of matching and comparing simulated and measured data.

The different techniques of numerical resolution of the equations in the model are not treated as a problem here. But it is clear that it is a common problem with all the fields in which numerical simulation is involved. Although the codes used for this purpose are evolving very quickly and the results can be very detailed and widely complete, these simulations present a remarkable grade of uncertainty. In the perspective of a more diffused industrial development of medium to low temperature geothermal fields, the numerical simulation can be a very useful instrument that must be connected with the strategic elaboration and environmental and economic sustainability of the design of a geothermal plant. Overall a relatively good agreement was obtained in the various cases between the measured and computed temperature profiles, but the matching of pressure profiles appeared to be more difficult. Even if the definition of the model and of the boundary conditions requires particular attention and experience in order to avoid wrong results, numerical simulation could be a good strategy for an integrated design of geothermal plants and for the prediction of the geothermal reservoir response and environmental impact of geothermal plants [71].

7. Conclusions

Numerical simulation is a fundamental and strongly interacting instrument for plant design. Different approaches to the numerical simulation of geothermal reservoirs operation are considered here, with reference to some case studies of geothermal fields and ground. The perspectives of numerical simulation of geothermal reservoirs as support to the design and sizing of geothermal plants are outlined. Models simulation is a powerful decision-making tool: it can provide useful indication about optimal sizing and sustainable management of geothermal utilization systems.

The behavior of geothermal reservoir and time variations of temperature, hydraulic head and pressure have to be estimated before the design of the plant. This is a general statement for each utilization in geothermal energy (steam plants, flash plants, district heating systems) but it is particularly meaningful in case of binary plants based on Organic Rankine Cycles (ORC), whose efficiencies and operations strongly vary according to small variations (concerning mass flow rate, temperature and pressure) of the characteristics of the resource.

Moreover the issues of scaling and of correct definition of reinjection strategy must be considered. The importance of connecting geological–geophysical and energy engineering background appears fundamental for the success of the exploitation of a geothermal field in order to sustain the geothermal fluid production rate over the whole lifecycle of the plant (in general higher than 15 years).

A review of different cases of numerical simulation from literature is considered and discussed. The state of the art methods and commercial softwares available for the simulation of geothermal fields are analyzed through the review of several geothermal fields and numerical models (ranging from medium temperature geothermal field to the well known cases of Larderello and Mt. Amiata, characterized by dry steam geothermal resource). Relatively good agreement was obtained in the various cases between the measured and computed temperature profiles; simulation of pressure profiles appears to be more difficult.

Even if defining the model and the boundary conditions requires particular attention and experience in order to avoid wrong results, numerical simulation could be a good strategy for an integrated design of geothermal plants and for the prediction of the geothermal reservoir response after a long time exploitation. Nevertheless, the following issues have to be considered in order to obtain reliable results.

- The geothermal phenomena simulation is complex, an interdisciplinary approach is therefore necessary.
- Software and codes often represent solver tools for the physical equations used.
- Case study experience and history matching is a fundamental background, and its study should be enhanced.
- Thermophysical parameters, boundary conditions, and meshing method strongly affect numerical simulation. Only a high accuracy level of the input data provides reliable results. According to the quality of information available, simplified models can be adopted.

An “integrated” approach to the complexity of the geothermal phenomena is still lacking. Geothermal energy is a particular renewable source: its use is sustainable only under particular conditions, which must be known particularly by investors and market players.

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